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Friction and wear properties of in-situ synthesized Al_2O_3 reinforced aluminum composites

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Abstract: Al−5%Si−Al_2O_3 composites were prepared by powder metallurgy and in-situ reactive synthesis technology. Friction and wear properties of Al−5%Si−Al_2O_3 composites were studied using an M−2000 wear tester. The effects of load, sliding speed and long time continuous friction on friction and wear properties of Al−5%Si−Al_2O_3 composites were investigated, respectively. Wear surface and wear mechanism of Al−5%Si−Al_2O_3 composites were studied by Quanta 200 FE-SEM. Results showed that with load increasing, wear loss and coefficient of friction increased. With sliding speed going up, the surface temperature of sample made the rate of the producing of oxidation layer increase, while wear loss and coefficient of friction decreased. With the sliding distance increasing, coefficient of friction increased because the adhesive wear mechanism occurred in the initial stage, then formation and destruction of the oxide layer on the surface of the sample tended to a dynamic equilibrium, the surface state of the sample was relatively stable and so did the coefficient of friction. The experiment shows that the main wear mechanism of Al−5%Si−Al_2O_3 composites includes abrasive wear, adhesive wear and oxidation wear.

Key words: Al−5%Si−Al_2O_3 composites; friction and wear; coefficient of friction; load; sliding speed

1 Introduction

Aluminum matrix composites (AMCs) play a significant role in metal matrix composites for their excellent properties, such as high specific strength and stiffness, good high temperature performance, resistance to fatigue and wear resistance, good damping property, low thermal expansion coefficient and excellent mechanical properties [1−4]. Among feasible AMCs, the particle reinforced aluminum matrix composites are widely used in the automotive and generator industry owing to their light weight, unique wear resistance and ease of preparation [5−7]. Recently, a number of researches on AMCs prepared by different methods were reported, especially about the wear properties. RAJMOHAN et al [8] concluded the mechanical and wear properties of hybrid aluminium metal matrix composites fabricated by stir casting method. The relationship between mass fraction and wear properties of mica was observed in this work. KHORRAMIE et al [9] produced aluminum matrix composites reinforced with Al_2ZrO_5 nano particulates by sol−gel auto-combustion method. The density, hardness and compression strength of the composites were discussed. ERARSLAN [10] researched the wear performance of in-situ aluminum matrix composite after micro-arc oxidation. Compared with the original state, the wear resistance of the composites increased by about 15 times after treatment. Compared with above methods, hot isostatic pressing in-situ fabrication method is better due to its convenient to form homogeneous material directly. GAO et al [2] prepared Al−Si−Al_2O_3 composites by hot isostatic pressing method. Although microstructure and properties of in situ fabricated Al−5%Si−Al_2O_3 composites were studied by CHENG et al [11], the critical frication and wear properties of AMCs still remain to be studied. $A1_2O_3$ is well known as the preferred reinforcement material. Moreover, Si is able to improve alloy liquidity, reduce the heat crack tendency and possess high hardness [1,12,13], which make it an attractive candidate for AMCs. If so, the wear resistance property of the aluminum matrix material added with $A1_2O_3$ and Si is better. So, we did the research in this

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work by combination of the hot isostatic pressing and in-situ fabrication methods to produce a super homogeneous AMCs with excellent wear resistance. The effects of contact load, sliding speed and long time continuous friction and wear on the friction and wear behaviors of this composite were studied by the single-variable experimental method, respectively. Morphological characterization and analytical investigations of the worn surface were performed on a scanning electron microscope (SEM) equipped with an energy disperse spectroscope (EDS) to explore the wear mechanism. The dominant wear mechanisms under different conditions were also discussed via the wear loss and morphologies as well as the composition of worn surface of composite.

2 Experimental

Alumina reinforced aluminum matrix composites (Al−5%Si−Al_2O_3) were fabricated by powder metallurgy and in-situ reactive synthesis technology. Specimens with dimensions of 10 mm × 10 mm × 15 mm were prepared by the wire-cutting to study the microstructure. Figure 1 shows the composite microstructure. It can be seen from it that the white lump is Al matrix. The brown particles distributed uniformly in the matrix are Al_2O_3. The gray spherical particles dispersed finely at the interface between alumina and aluminum matrix are eutectic silicon. Besides, the particles produced in the in-situ process tend to be free of contamination, which is able to improve the interfacial bonding strength [14].

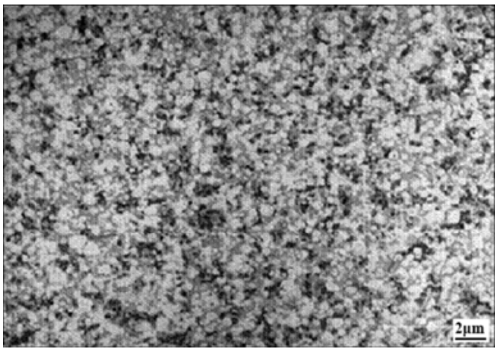


Fig. 1 Microstructure of Al−5%Si−Al_2O_3 composites

Friction and wear properties of Al−5%Si−Al_2O_3 composites were studied by an M−2000 model wear tester. Friction coefficient and wear loss were measured via mass loss method. After quenching and tempering, GCr15 steel was often applied to the grinding due to its high hardness, good abrasion resistance and high contact fatigue performance [15,16]. The hardness of the one used in this experiment was HRC (62±1) and grinding surface roughness was 0.8. The samples were cleaned with acetone, dried and then measured through sensitive weighing method by an analytical balance having an accuracy of 0.1 mg before and after the wear test in order to calculate the amount of wear loss. Wear surface and wear mechanism of Al−5%Si−Al_2O_3 composites were investigated by a Quanta 200 FE-SEM. The specific experimental procedures are as follows.

1) The test parameters were normal loads 30, 50 and 80 N with a constant sliding velocity of 0.84 m/s. The total sliding distance was 4500 m. The friction coefficient and wear loss were measured after each 500 m.

2) The test parameters were normal loads 50 N, sliding velocity of 0.21, 0.42, 0.63 and 1.05 m/s (namely the rotational speeds were 100, 200, 300 and 500 r/min, respectively). The friction coefficient was measured after each 200 m.

3) The test parameters were normal load 50 N, sliding velocity 0.84 m/s and the successive trials time 2.5 h (total sliding distance was 7500 m). The average friction coefficient was measured every each 5 min. After that, the SEM images of Al−5%Si−Al_2O_3 composite sample under a load of 50 N after continuous friction for 2.5 h were observed.

3 Results

3.1 Effect of contact load on friction and wear properties of Al−5%Si−Al_2O_3 composites

Through the test, the effects of different contact loads on friction and wear properties were investigated. Figure 2 shows the relationship between friction coefficient and load. The relationship between abrasion loss and slide distance under different loads is plotted in Fig. 3. Figure 4 illustrates the SEM images of Al−5%Si−Al_2O_3 composite samples under different loads.

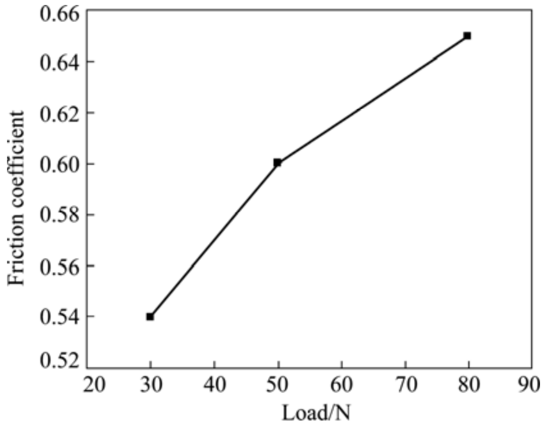


Fig. 2 Relationship between friction coefficient and load

Figure 2 depicts that the friction coefficient increases with the increase of load. The results are in good agreement with the well known Archard law of wear equation which records that the wear rate is

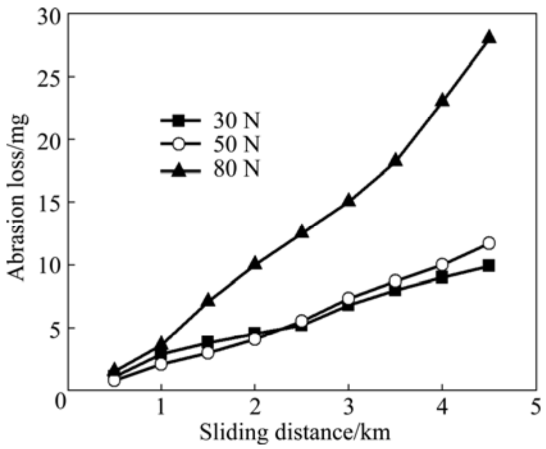


Fig. 3 Relationship between abrasion loss and sliding distance under different loads

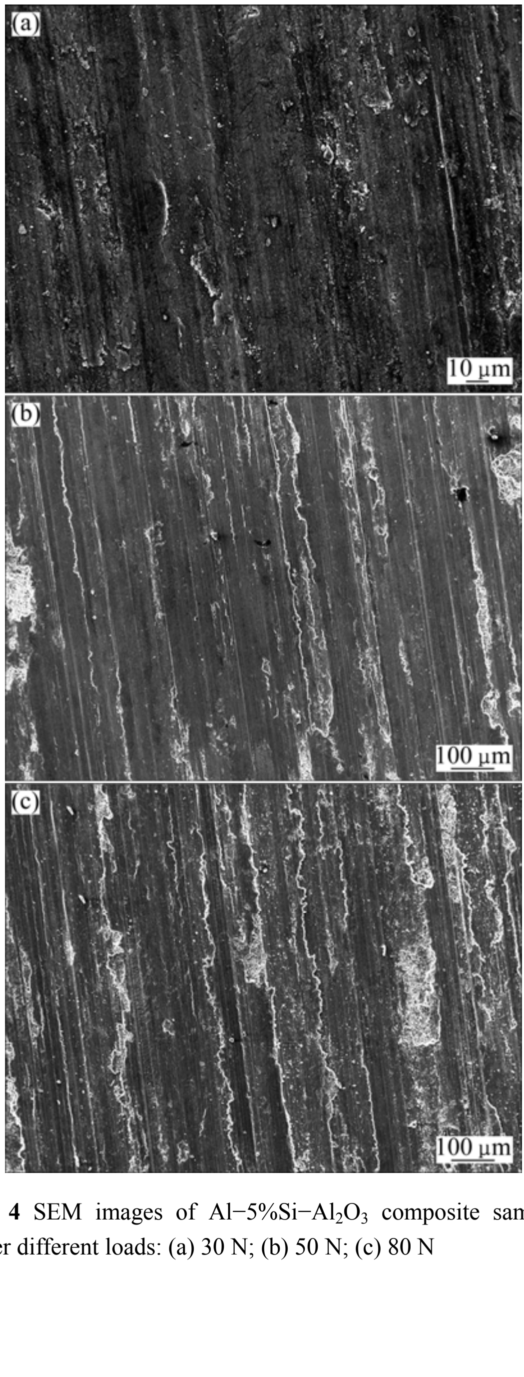


Fig. 4 SEM images of Al−5%Si−Al_2O_3 composite samples under different loads: (a) 30 N; (b) 50 N; (c) 80 N

proportional with the increase of applied load [17]. In addition, DINAHARAN and MURUGAN [14] also proved that the wear rate increased linearly with the increase of normal load. Figure 3 reveals that the wear loss is stable and less volatile between 30 and 50 N. However, the amount of wear loss increases significantly under 80 N and wear resistance of the sample is affected seriously. Continuous wear grooves and some relatively shallow but homogeneous scratches are seen in Fig. 4(a) at 30 N. A few cracks are clearly visible at the edge of grooves. Compared with Fig. 4(a), the grooves and cavities in Figs. 4(b) and (c) are deeper. At the same time, the proportion of cracks and delamination on the worn surface increases with the increase of load. In addition, the amount of wear loss increases gradually, so does the surface roughness. The above factors make the friction coefficient larger.

During sliding process, the mental flow was restricted in the presence of the secondary hard phases, such as Si and Al_2O_3 [18]. Simultaneously, Si addition had a significant effect on the interface bonding strength in the Al/Al_2O_3 joints [1,19]. Playing the role of load bearer during the sliding process, the hard particles can reduce the effective contact area between the friction pairs, which reduced the material's removal. When the soft base was worn under the external force, the particles would be exposed on the sample surface to bear the load mostly. It was conducive to prevent the soft matrix involved directly in the friction process. In addition, the inherent characteristic of in-situ fabrication method is able to produce a pure interface which improves the interfacial bonding strength [14]. Therefore, it is less likely for particles to strip from the substrate to exacerbate abrasive wear at low loads. As a result, the wear resistance of the composites was improved since its capacity resisted sticking and deformation [20,21]. At this moment, the dominant wear mechanism was abrasive wear which accompanied with mild oxidation wear and adhesive wear.

During repeated wear process, particle fragmentation occurred due to the formation of stress concentration and crack. As the third body, the wear debris formed under the high contact stress can damage the surface and cause detachment of oxides from surface of AMCs [22]. The higher the load was, the greater the extent of plastic deformation would be, which led to larger tribo-surface removal. Consequently, the contact area between the fiction pairs increased with load increasing. It is responsible for the wear rate increasing.

3.2 Effect of sliding speed on friction and wear properties of Al−5%Si−Al_2O_3 composites

Through the test, the effects of different sliding speeds on friction and wear properties were analyzed.

Figure 5 shows the relationship between friction coefficient and rotational speed. The relationship between abrasion loss and sliding distance with different rotational speeds is shown in Fig. 6. Figure 7 exhibits the SEM images of Al−5%Si−Al_2O_3 composite samples with different rotational speeds.

Figure 5 illustrates that the friction coefficient decreases when the sliding speed increases. Figure 6 shows that the wear loss decreases slightly with the increasing sliding speed. It is easy to find that the wear loss is very similar between the one with 300 r/min and another one with 500 r/min at the end of the test. This indicates that the material surface tends to be flat and the wear loss reaches a stabilization along with a certain sliding speed [5]. Figure 7 reveals that the delamination of sample surface significantly reduces with the increase of sliding speed. Also, grooves on surface become shallow and thin obviously. Meanwhile, cracks and pits decrease pronouncedly on the worn surface. All of these could be beneficial to the formation of oxide layer, which plays an important role in lubrication and

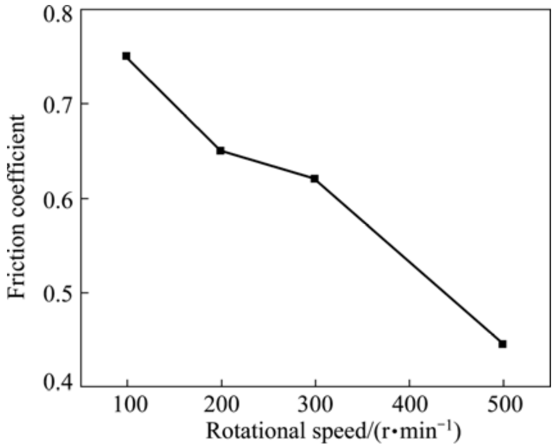


Fig. 5 Relationship between friction coefficient and rotational speed

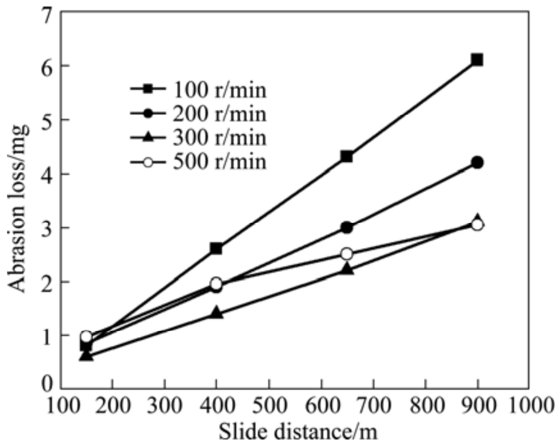


Fig. 6 Relationship between abrasion loss and slide distance with different rotational speeds

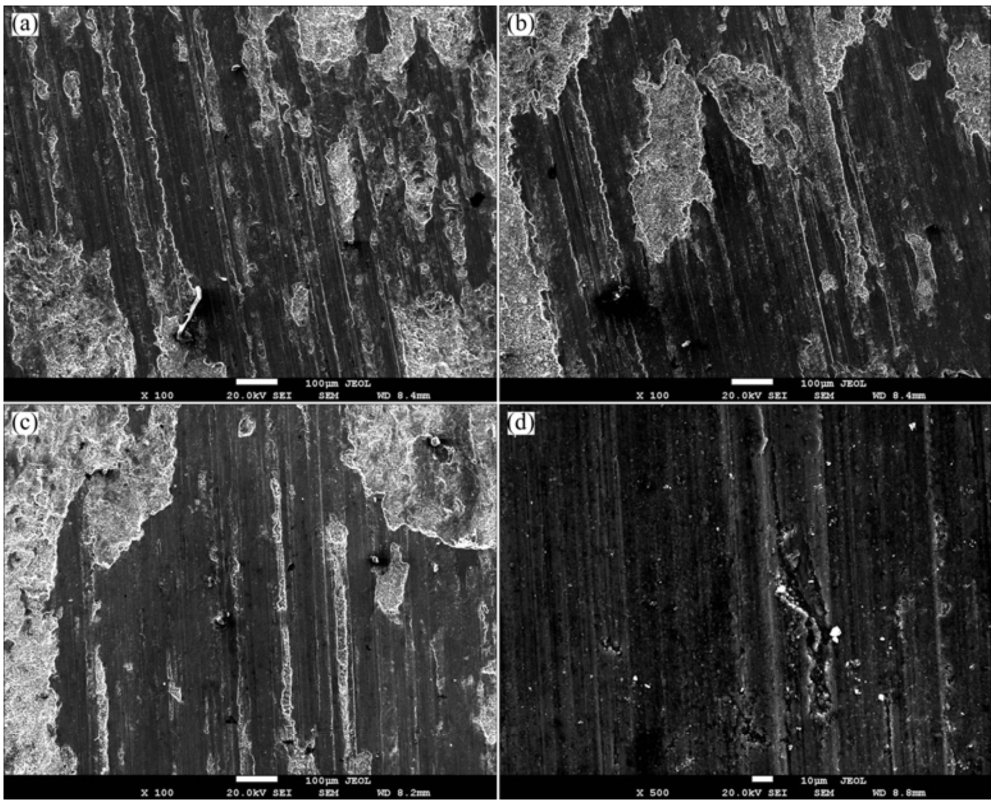


Fig. 7 SEM images of Al−5%Si−Al_2O_3 composite samples with different rotational speeds: (a) 100 r/min; (b) 200 r/min; (c) 300 r/min; (d) 500 r/min

antifriction. Consequently, both the wear rate and wear coefficient decrease gradually.

According to the empirical formula [23]:

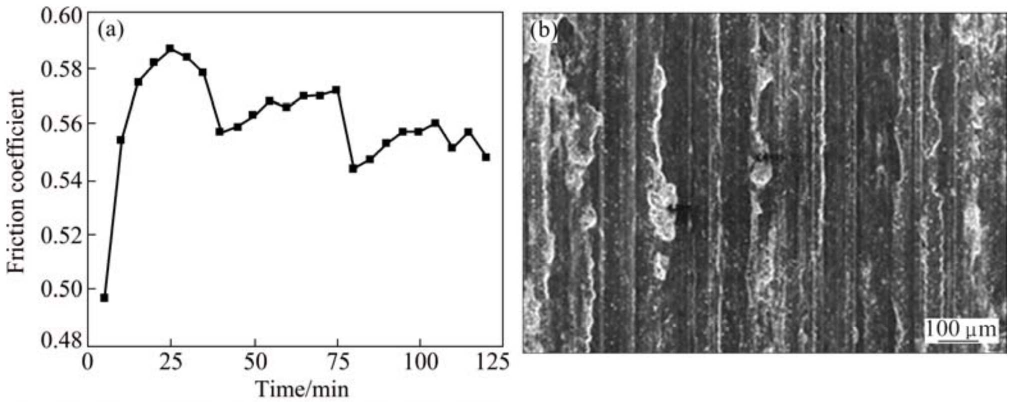
$$u = u_0 + e^{-cv} \quad (1)$$

where u_0 is the static friction coefficient considered a constant, v is the sliding velocity, and c is a constant, the coefficient of dynamic friction appeared an anti index ratio relationship. Hence, within a certain sliding speed range, the higher the sliding speed is, the smaller the friction coefficient is. The reasons are as follows. First, the work hardening produced by plastic deformation that became obvious with the increase of sliding speed, which led to the decrease in friction coefficient [24]. And then, within a certain degree, the increase of sliding speed would increase the amount of the oxides and enhance the self-lubricating [25]. It is evident from Fig. 7 that a complete oxide layer forms hardly on the worn surface under a low speed. And the amount of the oxides increases with the increase of sliding speed. The frictional heat could helpful to this phenomenon [24]. It is mainly because the oxidation reactions occurred more easily at a higher and proper temperature. Thereby, with a higher sliding speed, the oxide layer caused by the frictional heat [5] accumulated on the worn surface which gained an obvious lubrication. In addition, the elevated temperature could slightly reduce the abrasive wear by softening the asperity, which shallows the grooves and decreases the delamination of oxide layers. All these could reduce the friction coefficient to certain extent. However, with the increase of sliding distance, the contact area between the friction pairs increases due to the deformation and fracture as well as fragmentation of asperity leading to delamination enhanced, which causes a higher wear loss as shown in Fig. 6.

3.3 Effect of long-time continuous wear on friction and wear properties of Al−5%Si−Al_2O_3 composites

Generally speaking, materials are utilized under a continuous working state in practical application. Therefore, it is necessary to investigate the friction and wear characteristics of the composite material under the continuous work. Figure 8 shows the comprehensive analysis of Al−5%Si−Al_2O_3 composites for the continuous wear performance. Figure 8(a) shows the relationship between friction coefficient and time. Figure 8(b) reveals SEM image of Al−5%Si−Al_2O_3 composite sample under a load of 50 N after continuous friction for 2.5 h. Figure 8(c) shows SEM image of Al−5%Si−Al_2O_3 composite sample under a load of 50 N at a rotational speed of 400 r/min. Table 1 exhibits the analysis of chemical elements by EDS in Zone 1 and Zone 2 which are shown in Fig. 8(c).

Figure 8(a) indicates that the friction coefficient increases rapidly with the increase of the sliding distance within previous 30 min. Subsequently, it fluctuates between 0.54 and 0.57. It can be seen from Fig. 8(b) there are some deep grooves along the sliding direction. A lot of debris, lamellar shedding traces and pits appear



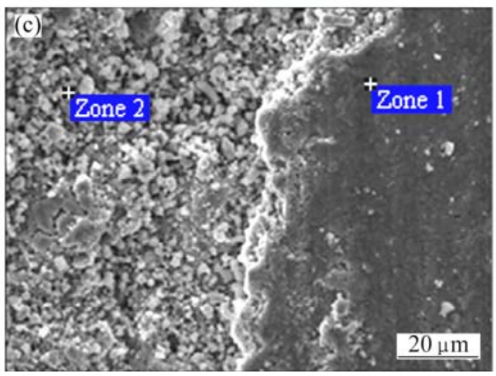


Fig. 8 Continuous wear performance analysis of Al−5%Si−Al_2O_3 composite: (a) Relationship between friction coefficient and time; (b) SEM image of Al−5%Si−Al_2O_3 composite sample under load of 50 N after continuous friction for 2.5 h; (c) EDS image of Al−5%Si−Al_2O_3 composite sample under load of 50 N at rotational speed of 400 r/min

Table 1 Analysis of chemical elements by EDS in Zone 1 and Zone 2 in Fig. 8(c)

Zone	Element	*w*/%	*x*/%
1	C	0.08	0.18
	O	23.93	42.63
	Al	32.39	34.23
	Si	1.39	1.41
	Fe	42.21	21.54
2	C	0.10	0.22
	O	23.76	40.16
	Al	42.29	42.39
	Si	1.75	1.69
	Fe	32.10	15.55
Total		100.00	−

on the sample surface. So the surface roughness worsens than before. Meanwhile, the delamination of the tribo-layer also exists. The EDS patterns of the worn surface exhibit the presence of C, O, Al, Si, Fe in Table 1. It confirms that the material transfer should happen between the friction pairs. Accordingly, the adhesive wear still exists during the whole friction and wear process.

At the beginning of the wear process, adhesive wear is dominant due to the plastic deformation of aluminum alloy matrix caused by the frictional heat, which softens the surface. The friction coefficient increases rapidly with the increase of time and the wear rate is tremendous. After a certain time, the adhesive wear weakens significantly on account of the exposure of enhanced phase hard particles on the surface of the matrix. Hence, abrasive wear becomes the primary wear mechanism, and the wear property is improved to a certain degree. Meanwhile, with good flow ability, Si plays an important role in lubrication and antifriction by uniformly dispersing in the Al matrix. Furthermore, as discussed earlier, Si addition enhanced the interfacial strength between reinforced particles and matrix [23], and also decentralized the shear stress of the material [25]. Consequently, it is more conducive to relieve wear condition [1]. During the long period of continuous wear process, the worn surface is mainly covered with smooth oxide layer to isolate the friction pairs and acts as lubrication. It is beneficial to the reduction of friction coefficient by effectively alleviating the wear of the composites. With the increase of sliding distance, however, the oxidation layer would be broken into pieces which caused the three-body abrasive wear. The volume fraction of the hard phase particles reduced with further wear, which caused the decline in wear performance and increase of the friction coefficient. In the light of the above, it was favorable to the improvement of tribological behavior when the formation and destruction of the oxide layer reached a dynamic equilibrium.

4 Conclusions

1) With the load increasing, the amount of wear loss on the surface increases. The major reason is abrasive wear mainly caused by Al_2O_3 particles giving birth to some shedding traces and grooves on the surface when the contact load increases. The oxide layer on the surface of the sample is seriously damaged by abrasives. Consequently, the friction and wear properties of the composites are affected seriously.

2) With the sliding speed increasing, the amount of wear loss decreases and the friction coefficient becomes small and tends to be steady. The main reason is that the surface temperature of the sample increases when the sliding speed increases. Thereby, the oxide layer plays a role in lubricating formed easily on the sample surface. It is beneficial to decreasing the friction coefficient.

3) The friction and wear properties are stabilized when the formation and destruction of the oxide layer reach a dynamic equilibrium after the long continuous friction and wear. The adhesive wear still exists during the whole continuous friction and wear process. The friction coefficient is more stable than before after a long continuous friction and wear.

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原位合成 Al_2O_3 增强铝基复合材料的摩擦磨损性能

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摘 要：通过采用粉末冶金和原位合成技术相结合的近净成形技术制备 Al−5%Si−Al_2O_3 复合材料，并运用 M−2000 摩擦磨损试验机对该复合材料的摩擦磨损性能进行研究。通过单一变量比较法分析载荷和滑动速度对 Al−5%Si−Al_2O_3 复合材料摩擦磨损性能的影响，同时对长时间连续磨损下该材料的摩擦性能进行研究。通过扫描电子显微镜对 Al−5%Si−Al_2O_3 复合材料的磨损表面进行观察，并分析其磨损机制。结果表明，随着载荷的增大，试样的磨损量和摩擦因数均增加；随着滑动速度的增大，试样表面的升温使得产生氧化层的速率增加，试样的磨损量和摩擦因数均减少。在长时间的连续磨损过程中，由于初始时发生粘着磨损，试样的摩擦因数随着滑动距离的增大而增大。然后，试样表面氧化层的形成和破坏趋于动态平衡，试样表面相对稳定，其摩擦因数也随之趋于平稳。铝基复合材料的磨损机制主要为磨粒磨损、粘着磨损和氧化磨损。

关键词：Al−5%Si−Al_2O_3 复合材料；摩擦磨损；摩擦因数；载荷；滑动速度

(Edited by Xiang-qun LI)